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Investigation on the development potential of rooftop PV system in Hong Kong and its environmental benefits

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A B S T R A C T

Solar photovoltaic (PV) technology is expected as one of the ideal renewable energy resources which can be used in large scale in Hong Kong. This paper presents an in-depth investigation into the development potential of rooftop PV system in Hong Kong and its environmental benefits as well. The potential installation capacity of rooftop PV systems is estimated to be 5.97 GW_p, and the annual potential energy output is predicted to be 5981 GWh accordingly. The annual energy yield can account for 14.2% of the total electricity used in Hong Kong in 2011. In addition, about 3,732,000 t of greenhouse gas (GHG) emissions could be avoided yearly by the replacement of the equivalent local electricity mix. For environmental benefits, the investigation results showed that the energy payback time (EPBT) and the GHG emission payback time (GPBT) of different types of rooftop PV systems in Hong Kong ranged from 1.9 to 3.0 and 1.4 to 2.1 years, respectively, both of which are far less than the systems' lifespan of 30 years. The energy yield ratio (EYR) ranged from 10.0 to 15.8, which indicates that the rooftop PV systems could generate at least 10 times the energy requirement during the system's lifetime. Although the current PV system installation cost is relatively high in Hong Kong, PV electricity is expected to fully compete with traditional electricity modes in the near future if appropriate subsidies are provided by the local government, carbon credits benefits are considered and installation cost can be further reduced. Thus, more proactive energy policies and aggressive development targets for PV technology should be set by the government. The findings presented in this paper are expected to provide a theoretical basis for local policy makers to set reasonable renewable energy policies, development targets as well as subsidies for PV technology in Hong Kong.

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Nomenclature

Abbreviation

AC	alternative current
API	air pollution index
a-Si	amorphous silicon
BIPV	building integrated photovoltaic
BOS	balance of system
CAD	computer aided design
CDM	clean development mechanism
CdTe	cadmium telluride
CER	certified emission reduction
CIGS	copper indium gallium selenide
EMC	energy management contract
EPBT	energy payback time
EYR	energy yield ratio
FIT	feed-in-tariffs
GHG	greenhouse gases
GIS	geographic information systems
GPBT	greenhouse-gas payback time
LCA	life cycle assessment
LCOE	levelized cost of energy
mono-Si	mono-crystalline silicon
multi-Si	multi-crystalline silicon
PM10	respirable suspended particulates
PV	photovoltaic
SMA	system advisor model
STC	standard testing conditions

Symbols

D	reserved distance between rows
H	installation height of PV module
L	projection of sunlight
W	width of PV module
θ	angle of incidence
β	slope angle of PV modules
γ	solar azimuth angle
δ	solar declination
ω	hour angle
α	solar altitude angle
φ	latitude
θ_z	zenith angle
ρ_o	ground reflectance
Q_{ic}	initial cost
Q_o	annual operation and maintainance cost
γ_{dr}	real discount rate
R_v	residual value
η_{dr}	PV system's degradation rate
η_{stc}	PV module's energy conversion efficiency in standard testing conditions
λ	performance ratio of PV system.

Subscripts

$A_{act.}$	potential total active area of PV modules, (m^2)
$A_{occu.}$	installation occupancy area of a single PV module, (m^2)
$A_{pot.}$	potential PV-suitable rooftop area, (m^2)
A_{pv}	area of a single PV module, (m^2)
$E_{BOS,E}$	energy requirement of the balance of system components, (MJ)
Egen	equivalent primary energy savings due to annual electricity generation by the PV system, (MJ)
E_i	energy output of a PV system in the first year, (MJ)
E_{input}	energy requirement of PV modules during the life cycle, (MJ);
E_{output}	equivalent energy savings due to PV system's annual electricity generation, (MJ).
$E_{potential}$	annual potential energy output of rooftop PV systems, (GWh)
G_{bh}	horizontal surface beam solar radiation, (W/m^2)
G_{bt}	tilted surface beam solar radiation, (W/m^2)
G_{dh}	horizontal surface diffuse solar radiation, (W/m^2)
G_{dt}	tilted surface diffuse solar radiation, (W/m^2)
$G_{optimal}$	annual total solar radiation incident on the optimum tilted angle, (kWh/m^2)
G_r	reflected solar radiation, (W/m^2)
G_{th}	horizontal surface total solar radiation, (W/m^2)
G_{tt}	tilted surface total solar radiation, (W/m^2)
GHG_{BOS}	embodied GHG emission of BOS components
GHG_{output}	annual GHG emission amounts in the cases where local mix power plants generate the power equivalent to that of the PV systems
GHG_S	embodied GHG emissions of PV modules
L_{PV}	designed lifespan of the PV system, (year)

1. Introduction

In 2010, total energy end-use in Hong Kong was about 276,950 TJ, among which renewable energy, including solar energy, wind energy, biogas and bio-diesel, accounted for only 0.6%, and the remainder was derived from fossil fuels (coal, oil, and natural gas) [1]. The extensive burning of fossil fuels results in massive emissions of greenhouse gases (GHG) and is thought to be a main contributor to environmental pollution problems. Currently, air pollution problems have become one of the major obstacles restricting international competitiveness of Hong Kong. Two of the urgent environmental pollution problems which need to be harnessed are local street-level pollution and regional smog [2]. In 2011, the number of days that the air pollution index (API) exceeded 100 rose to 175 in Hong Kong [2]. This API indicates a very high air pollution level. The street-level pollution problem is mainly caused by vehicles emissions, while the regional smog problem is mainly caused by fossil fuel emissions from power plants. The electricity mix in Hong Kong is constituted of 23% nuclear power imported from Mainland China and 77% traditional thermal power generated by the local power plants. Among the local thermal power, about 71% is generated by coal-fired power plants and the other 29% is generated by natural gas power plants [3]. In 2010, SO_2, NO_X and respirable suspended particulates (PM_{10}) emitted by the thermal power plants respectively accounted for 50%, 25% and 16% of the total emissions in Hong Kong [3]. Therefore appropriately reducing fossil fuel power plant operation could effectively mitigate further environmental pollution.

Additionally, Hong Kong is short of natural resources, especially fossil fuel resources, all of which are imported. The rapid growth of global energy demand in recent years has already resulted in price rises in this area and may also lead to a shortage of energy supply in the near future. Further imbalance of energy supply and demand globally will negatively affect the energy security of Hong Kong, which as indicated above is dependent on imported

fossil fuels. Therefore, in order to cope with the potential challenges of both energy shortage and environmental pollution, the solution seems likely to be found in the sustainable energy area. In Hong Kong the available renewable energy sources are mainly limited to solar energy and wind power. Compared with wind power which needs much maintenance and occupies a large amount of land, solar photovoltaic technology is almost maintenance-free and can be integrated with an envelope of buildings, especially the roof, to create a building integrated photovoltaic system (BIPV). Thus, because of the high building density and limited land resource, BIPV systems can be suitable and feasible for cities like Hong Kong. They are expected to become one of the few ideal choices for Hong Kong's renewable energy development in future.

Since BIPV technology has the potential of large-scale application in Hong Kong, many people, especially the policy makers, may be very interested in finding answers to the following questions: (1) how much PV capacity can be installed on the roofs of building? (2) how much electricity can be generated yearly from these rooftop PV systems? (3) what potential proportion of the total electricity can be provided by PV electricity generated by rooftop PV systems in Hong Kong? Therefore, this study aims to provide answers to these questions.

The potential of BIPV systems has been studied by researchers in many countries and regions since the emergence of this technology. The methods aiming at determining the roof-top PV potential were reviewed [4]. Gutschner et al. [5] evaluated the BIPV technical potential in member countries of International Energy Agency (IEA) by using solar-architecturally PV suitable area per capita. It was found that the PV electricity production potential varied from 15% to 60% in different countries depending on the solar radiation resources, PV suitable area per capita and population size. In order to estimate the PV-suitable rooftop area in the United States (US), Denholm and Margolis [6] firstly calculated the building rooftop area in each state by scaling the total floor space data with the number of floors in each building class, the building rooftop area would then be translated into available PV-suitable rooftop area by taking into account the impact of rooftop obstructions, shading and other constraints. The results using the above estimation method indicated that all building rooftops in the United States could host about a 661 GW_p installation capacity if the PV modules were installed rack-mounted and had conversion efficiency of 13.5% [6]. Pelland and Poissant [7] assessed the BIPV development potential in Canada based on the ground floor surface areas. The potential installation capacity was about 73 GW_p and the corresponding electricity production was 72 TWh, which accounted for 29% of the annual electricity consumption in Canada. Technical potential for PV on buildings in the EU-27 member states was estimated [8], and the PV suitable roof area was calculated by multiplying population size with the average roof area per capita. The BIPV installation potential in EU was estimated to be 951 GW_p. These PV systems can totally generate 840 TWh yearly, which accounts for 22% of the expected electricity demand in European by 2030. Recently, the European Photovoltaic Industry Association (EPIA) estimated the roof-top PV potential in Europe, the US and Japan. The PV electricity production potential was estimated to respectively account for 59%, 42% and 51% of the total residential electricity consumption in these countries and region [9].

An economic assessment for BIPV systems, based on cost-resources curves, was carried out [4]. The results showed that the PV cost varied with the increasing installation capacity. Specifically, it varied from 9 to 12 ¢€/kWh in Canary Islands of Spain in 2012. The trade-off between environmental benefits and economic costs of BIPV systems was assessed in the United Arab Emirates (UAE) [10]. It was found that the BIPV systems can make a significant reduction of greenhouse gases, but its economic viability depended on the capital cost, system efficiency and electricity tariff. Thus, the subsidies and favorable feed-in tariff (FIT) should be implemented to boost PV large-scale application. An economic analysis was also conducted for the decentralized BIPV systems in cities of Gulf Corporation Council (GCC) countries. The results showed that the BIPV technology was not a cost-effective option for the GCC countries based on that time PV system cost, conversion efficiency and electricity tariff. The BIPV technology would be feasible only if either the PV system's cost was reduced drastically or the conventional electricity tariff was increased substantially [11]. Fortunately, the PV module's cost has declined sharply in recent years. Specially, it dropped from $\$4.2/W_p$ in that time to less than $\$1/W_p$ at present.

Besides, some studies also focused on the PV potential assessment at small scales instead of national scale, such as island, community, school, and university campus. National Renewable Energy Laboratory (NREL) developed a customized software, named IMBY-Kaua'i tool, to assess the solar resources and PV potential on the island of Kaua'i, Hawai'i [12]. This tool allowed the user to draw a polygon on a roof or open ground area and then estimated the PV suitable area. Combined with hourly satellite solar radiation information and the PVWatts performance model, this tool can finally figure out the annual potential electricity production of any polygon area. However, one limitation of this tool is that it only allows the user to analyze one PV site at a time, thus it is not suitable for assessing PV potential in large area. Talavera et al. [13] analyzed the energy and economic potential to integrate small PV systems with buildings in the University of Jaen in Spain. Two effective tools, viz. the orthopicture tool and the PV-Sys software, were used to identify PV suitable area and figure out the shading problem caused by surroundings or PV modules, and to estimate the annual electricity generation as well. The results showed that the potential PV electricity production could meet about 25% of the annual electricity consumption of the University. In addition, the economic analysis in this paper also revealed that the levelized cost of electricity (LCOE) was influenced by several parameters, especially the initial investment, the energy yield and the nominal discount rate. However, although the PV-Sys software can well figure out the shading problem for small scale PV systems, it may not be suitable for large scale.

Thuvander and Tornberg [14] investigated the potentials of solar energy application in roof-top of buildings in Goteborg of Sweden by using geographic information systems (GIS) method. Combined with local base maps which contain computer aided design (CAD) files with 3D information, this method can identify the real roof constructions, inclinations and orientations of the buildings, and then calculate the suitable roof-top areas for solar energy application. However, the authors also pointed out that a number of calculation errors may occur for large area investigation in an automated way if the data quality of base maps is low. Thus, this technology is highly depended on the availability of high quality base maps data. In addition, this method is not yet suitable for investigating a large number of buildings with more complex roof structures [14]. In addition, Close et al. [15] assessed the potential of using PV systems in Hong Kong schools, and the case study showed that PV systems can contribute about 10% of the total electricity consumption for a typical primary school in Hong Kong.

From the above literature review, it can be seen that the previous studies mainly focused on using different methods to assess the technical potential of roof-top PV systems. Actually the main difference between these methodologies is how to evaluate the PV suitable roof area. The common methods for evaluating the PV suitable roof area can be classified into three types, viz. assuming the roof area ratio per capita, establishing correlation

between the population density and roof area, as well as aided by GIS. Based on the previous studies, this paper assessed the technical potential of roof-top PV systems in Hong Kong by using the methodology of solar-architectural rules of thumb, which is easy and suitable for potential assessment in large scale.

This study aims to conduct a comprehensive analysis and evaluation on the feasibility and potential of roof-top PV systems in Hong Kong from the technical, economic, energy and environmental points of view. Except for the technical potential, three other important issues, viz. installation cost, energy gain and the subsequent environment improvement, all play an important part in determining whether the PV application is a viable option for customers. Prior to further promotion of PV applications in Hong Kong, these issues need to be addressed and the results should be presented to the public to ensure the understanding of the potential value of such systems.

With the decline of raw material costs as well as those resulting from the effect of the production of PV modules on a large-scale, the cost of PV systems has reduced significantly over recent years. The PV module's price has fallen by $2.1/$W_p$ between 2008 and 2011 [16]. In Germany, the average installation cost reduced to $2.32/$W_p$ (€1.751/W_p) by the end of the second quarter of 2012 [17]. The German solar industry association estimated that in Germany solar power cost would be lower than that of retail electricity by the end of 2012 and then it would be fully competitive with traditional electricity without any subsidies by 2017 [18]. In recent years, it has also seen a rapid development of PV systems in the US. In 2011, the annual installed capacity in the US reached 1.85 GW_p, and the installation cost of rooftop PV systems ranged from $5.02 to 5.71/$W_p$ corresponding to an unsubsidized LCOE of $0.2/kWh [16,19–20]. Although the costs of hardware such as PV modules and inverters are almost the same in different countries; however, considerable differences are found in the “soft cost”, such as labor costs, operating overhead, supply chain costs, coordination fees, as well as permitting, interconnection and inspection costs. This cost alone results in a big difference in the total installation cost in different countries. A discussion with many PV system suppliers and contractors to analyze costs of PV systems installed in Hong Kong revealed a typical installation cost, which is presented in this paper. Based on this installation cost, the LCOE of PV electricity in Hong Kong is calculated to assess its economic feasibility and competitiveness compared with that of the traditional electricity. In this study the results of the investigation into installation cost and LCOE is suggested as a basis for local policy makers when considering incentive subsidies to be given for PV systems.

Photovoltaic technology almost does not consume energy and emit greenhouse gas during operating. However, a large amount of energy is consumed and subsequently GHG are emitted during its life cycle, such as in the manufacturing, transportation, installation, and recycling processes. Some have argued that the total energy yield of a PV system is probably insufficient to compensate for the energy consumption during its lifetime. Therefore PV technology may not be regarded as a sustainable energy resource [21–22]. It is difficult to accurately estimate the GHG emission rate and energy payback time (EPBT) of a PV system, because these indicators are influenced by many factors, such as the PV module manufacture technology, local solar energy resources, the module's energy conversion efficiency and the installation method (orientation, tilted angle) and so on. Thus the energy and environmental benefits would be considerably different for the same PV system, but installed in different regions. Although much literature concerning PV systems' EPBT and GHG emission rates have been published, few studies focus on that of rooftop PV systems in Hong Kong. Hence, a further aim of this study is to investigate the energy yield and environmental benefits of PV system in Hong Kong using the life cycle assessment (LCA) method to further understand the system's potential for energy saving and GHG mitigation. As indicated above an understanding of such findings is important for policy makers to set GHG emission reduction and renewable energy development targets.

2. Development potential of rooftop PV systems

2.1. PV-suitable rooftop area

An assessment of rooftop PV potential usually starts with determining the rooftop area available upon which to install PV systems. However there is little direct statistical information regarding PV-suitable rooftop areas. Gutschner et al. [5] introduced a method to estimate the PV-suitable rooftop area from a buildings' ground floor area. The details of the procedure are illustrated in Fig. 1. Firstly, the ground floor area is transferred into the gross roof area by using a ratio “gross roof area vs. ground floor area”. The potential PV-suitable rooftop area can then be calculated based on the gross roof area by using factors of solar suitability and architectural suitability. Usually, the ratio “gross roof area vs. ground floor area” and the factors of solar suitability and architectural suitability can be determined by rule of thumb. These three factors were assumed to be 1.2, 0.55 and 0.6 in [5]. Based on these three factors, the ratio: “potential PV-suitable rooftop area vs. ground floor area” (also named utilization factor) was calculated to be 0.4 [5].

In order to check whether the above methodology and rule of thumb are suitable for Hong Kong's situation, an on-site feasibility study was carried out. The PV-suitable rooftop area of two kinds of buildings (Hotel and Commercial) was evaluated by detailed measurements such as the active rooftop area. The measurement results were compared with the results estimated by the Solar-Architectural rules of thumb. It was found that the measurement results were always larger than the estimated results by about 10–15% when the utilization factor (the ratio “potential PV-suitable rooftop area vs. ground floor area”) was chosen as 0.4.

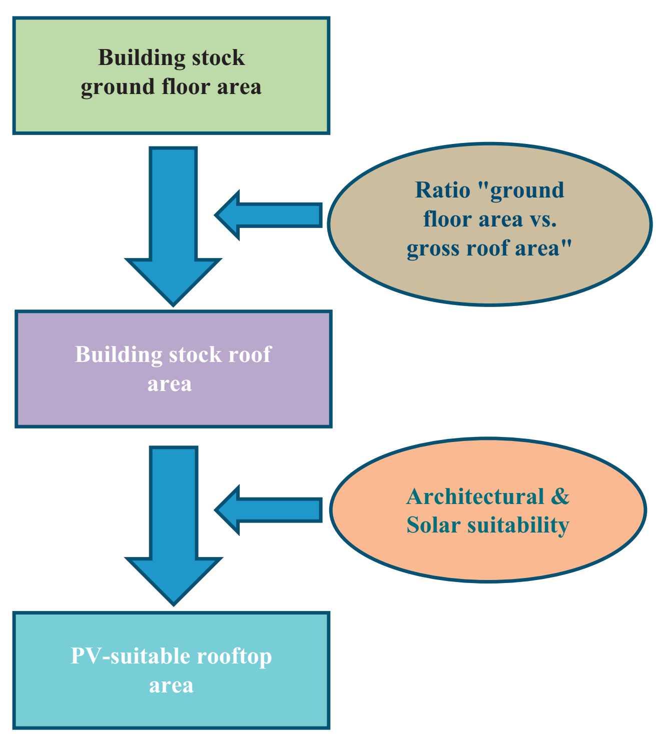

Fig. 1. The procedures to estimate the potential PV-suitable rooftop area.

Table 1
The potential PV-suitable rooftop area in Hong Kong.

Ground floor area	117 km^2
Ratio “gross roof area/ground floor area”	1.2
Gross roof area	140 km^2
Architectural suitability factor	0.7
Architecturally suitable roof area	98 km^2
Solar suitability factor	0.55
The potential PV-suitable rooftop area	54 km^2

One possible explanation for this is that the architectural suitability factor is larger than 0.6 in Hong Kong. Thus a modification was conducted based on the on-site survey. The architectural suitability factor of 0.7 was adopted instead of 0.6 and the utilization factor of 0.6 was used instead of 0.4 in Hong Kong for estimating the potential PV-suitable rooftop area. The total ground floor area of all buildings in Hong Kong is about 117 km^2, of which, residential buildings account for 65%, public buildings account for 21%, and industry and commercial buildings account for the remaining 14% [23]. From the above figures, the potential PV-suitable rooftop area in Hong Kong can be easily calculated and the results are presented in Table 1.

2.2. The optimum tilted angle for rooftop PV installation

The energy output of a PV system is directly determined by solar irradiation received by the PV modules; thus such modules should be installed with the optimum orientation and titled angle to maximize the PV system' energy output. Most observatories, however, only offer total solar radiation data on a horizontal plane. Thus, it is necessary to transfer the total solar radiation on a horizontal surface into the incident solar radiation on any sloping surface and then find the optimum tilted angle for rooftop PV installation. The hourly total solar radiation incidence on a tilted surface, G_{tt} (W/m^2), can be expressed as follows:

$$G_{tt} = G_{bt} + G_{dt} + G_r \tag{1}$$

where G_{bt} is the hourly beam solar radiation incidence on a tilted surface, W/m^2; G_{dt} is the hourly diffuse solar radiation incidence on a tilted surface, W/m^2; and G_r is the hourly reflected solar radiation, W/m^2. G_{bt} and G_r can be given by the following equations, respectively [24].

$$G_{bt} = G_{bh} \times R_b = G_{bh} \times \frac{\cos\,\theta}{\cos\theta_z} \tag{2}$$

$$G_r = \frac{\rho_o}{2} G_{th}(1 - \cos\,\beta) \tag{3}$$

where G_{bh} is the beam radiation incidence on the horizontal surface, it can be extracted from the total horizontal radiation of G_{th} (provided by the Observatory); θ is the angle of incidence; β is the slope angle of PV modules; θ_z is the zenith angle; ρ_o is the ground reflectance.

Although several models, such as the Perez Model [25–26], Hay and Davies Model [27], Reindl Model [28] and Li model [29], are used to simulate the diffuse solar radiation on any tilted surface, this procedure is still the most difficult part to simulate and a relatively big error may be generated if the chosen model is not suitable for the local weather condition. Lu and Yang [30] compared the above four models with different tilted angles and orientations using Hong Kong weather data. Results showed that for PV modules with a lower tilted angle, the Perez model can provide high accuracy results. Thus, in this study, the Perez model is adopted to simulate the diffuse solar radiation incidence on any tilted surface. In the Perez Model, the diffuse solar radiation

Table 2
The total solar irradiance incidence on various south-facing orientated tilted surfaces, G_{tt} ($kWh/m^2/yr$).

Year	Tilted angle							
	18°	19°	20°	21°	22°	23°	24°	25°
1998	1237.3	1237.8	1238.1	***1238.2***	1237.9	1237.4	1236.6	1235.5
1999	1335.8	1337.4	1338.6	1339.5	1340.1	***1340.5***	1340.5	1340.2
2000	1347.5	1348.2	1348.6	***1348.7***	1348.5	1348.0	1347.2	1346.1
2001	1287.7	1289.2	1290.4	1291.4	1292.0	***1292.4***	1292.4	1292.2
2002	1301.3	1302.1	1302.6	1302.9	***1302.9***	1302.5	1301.9	1301.0
2003	1391.8	1393.4	1394.7	1395.7	1396.3	***1396.7***	1396.7	1396.4
2004	1372.2	1373.6	1374.7	1375.5	1376.0	***1376.2***	1376.1	1375.7
2005	1235.3	1236.4	1237.2	1237.8	1238.1	***1238.2***	1237.9	1237.4
2006	1343.4	1344.9	1346.1	1347.0	1347.6	***1347.9***	1347.9	1347.6
2007	1443.5	1444.9	1446.0	1446.8	1447.3	***1447.4***	1447.2	1446.6
Average	1329.6	1330.8	1331.7	1332.4	1332.6	***1332.7***	1332.4	1331.9

incidence on a tilted surface can be calculated by [25–26]

$$G_{dt} = G_{dh}\left[(1 - F_1)\left(\frac{1+\cos\,\beta}{2}\right) + F_1\frac{a}{b} + F_2 \sin\,\beta\right] \tag{4}$$

where G_{dh} is the diffuse solar radiation incidence on the horizontal surface, it can be extracted from the total horizontal solar radiation, G_{th}.

In order to maximize the annual solar radiation received by the rooftop PV module, a FORTRAN program was developed based on the above mathematic models to find the optimum tilted angle for rooftop PV installation. The simulated solar irradiance incidence on various tilted surfaces of south-facing orientation from 1998 to 2007 is given in Table 2. It is found that the optimum tilted angle for rooftop PV installation in Hong Kong is 23 degree and accordingly the largest average solar radiation is about 1333 $kWh/m^2/yr$ during the ten years. Thus, the rooftop PV system in Hong Kong is recommended to be installed with this optimum tilted angle to maximize the annual energy output. While for one specific year between 1998 and 2007, the optimum tilted angle varied with the annual weather data. Normally it is almost around 22 ± 1 degree which is very close to the latitude of Hong Kong. From this table, it is seen that the annual solar radiation is significantly influenced by the weather conditions, the largest annual solar radiation (1447.4 $kWh/m^2/yr$ in the year of 2007) is larger than that of the least example (1238.2 $kWh/m^2/yr$ in the year of 1998) by 210 $kWh/m^2/yr$, which indicates that it is more reasonable and accurate to use the long-term average solar irradiation (such as ten years or more) when simulating the PV system's energy output.

2.3. Installation potential of rooftop PV systems

In order to maximize the energy output of rooftop PV systems in limited PV-suitable roof areas, high efficiency PV modules should be used. In this study, a STP260S mono-crystalline PV module made by Suntech of China was chosen as an objective module. Its characteristics are listed in Table 3 [31].

In all previous studies concerning the estimation of potential PV installation capacity, the issue of probably partial shading caused by the front rows of PV modules was not considered. In a real system however, certain space has to be reserved between the front and back rows to eliminate such partial shading effect. In this study, the array distance between the front and back rows was determined by making sure that there is no partial shading caused by the front row of PV modules between 9:00 AM and 3:00 PM during the winter solstice in Hong Kong. Fig. 2 shows the schematic diagram to calculate the array distance between the front and back rows of PV modules. From this figure, it is seen that

the array distance of the PV modules installed with the optimum tilted angle (23° in Hong Kong) can be calculated as follows:

$$D = \cos\gamma \times L \tag{5}$$

where D is the reserved distance between the front and back rows; γ is the solar azimuth angle at 9:00AM during the winter solstice in Hong Kong. This can be calculated by Eqs. (6) and (7) [24]; L is the projection of sunlight on the roof horizontal surface.

$$\sin\gamma = \cos\delta \sin\omega / \cos\alpha \tag{6}$$

$$\gamma = \arcsin(\cos\delta \sin\omega / \cos\alpha) \tag{7}$$

where δ is the winter solstice solar declination; ω is the winter solstice hour angle at 9:00AM; α is the solar altitude angle, which can be calculated as follows [24]:

$$\sin\alpha = \sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega \tag{8}$$

$$\alpha = \arcsin(\sin\varphi \sin\delta + \cos\varphi \cos\delta \cos\omega) \tag{9}$$

where φ is the latitude of Hong Kong. The projection of sunlight on the roof horizontal surface can be calculated by

$$L = H / \tan\alpha \tag{10}$$

$$H = W \times \sin\beta \tag{11}$$

where H is the installation height of PV module; W is the width of PV module; and β is the optimum tilted angle.

All parameter values and the calculation results are presented in Table 4. It is seen that in order to make sure there is no partial shading between the front and back rows of PV arrays during the winter solstice in Hong Kong, the layout of PV arrays should be kept at a distance of 514 mm between the front and back rows when the PV modules are installed with the optimum tilted angle.

After taking the reserved array distance into account, installing a single objective PV module (STP260S) would occupy about 2.35 m^2 of the rooftop areas. The total active area of the rooftop PV modules can be calculated by the following equation:

$$A_{act.} = \frac{A_{pot.}}{A_{occu.}} \times A_{pv} \tag{12}$$

where, $A_{act.}$ is the potential total active area of PV modules; $A_{pot.}$ is the potential PV-suitable rooftop area in Hong Kong; $A_{occu.}$ is the installation occupancy area of a single PV module; A_{pv} is the area of a single PV module. For rooftop PV application, the potential total active area of PV modules installed with the optimum tilted angle of 23° was calculated to be 37.4 km^2. Thus the potential installation capacity of rooftop PV system is estimated as 5.97 GW_p in Hong Kong. The potential of annual energy output of rooftop PV

Table 3
Electric parameters of the STP260S mono-Si PV module.

Parameters	Values
Solar cell (L×W)	Monocrystalline silicon 156 × 156 mm
Maximum power at STC (P_{max})	260 W
Optimum operating voltage (V_{mp})	30.9 V
Optimum operating current (I_{mp})	8.42 A
Open circuit voltage (V_{oc})	37.7 V
Short circuit current (I_{sc})	8.89 A
Module efficiency	16.0%
No. of cells	60 (6 × 10)
Dimensions (L×W×T)	1640 × 992 × 35 mm

Table 4
The parameter values and results for calculating the array distance.

Parameters	Values and results
Solar declination (δ)	−23.5°
Hour angle (ω)	45°
Optimum tilted angle (β)	23°
Latitude (φ)	22.25°
Width of PV module (W)	992 mm
Solar altitude angle (α)	26.5°
Solar azimuth angle (γ)	46.5°
Installation height (H)	372 mm
Projection of sunlight (L)	746 mm
Distance between front-back rows (D)	514 mm

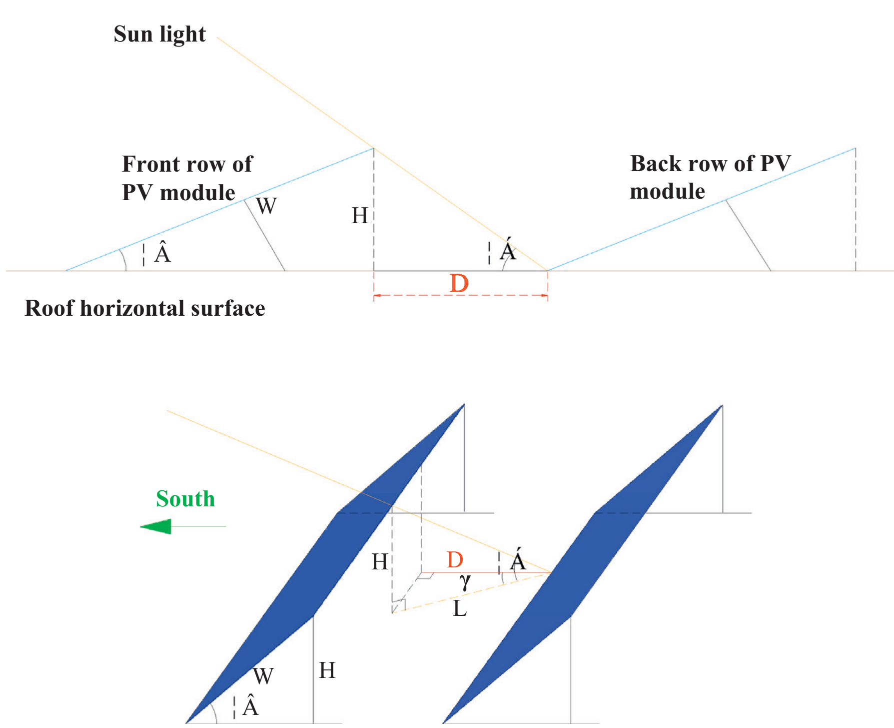

Fig. 2. The schematic diagram to calculate the array distance.

system can be briefly estimated by the following equation:

$$E_{potential} = A_{act.} \times G_{optimal} \times \eta_{stc} \times \lambda \quad (13)$$

where $E_{potential}$ is the Hong Kong annual potential energy output of rooftop PV systems; $G_{optimal}$ is the annual total solar radiation received by the PV modules installed with the optimum tilted angle, about 1332.7 kWh/m^2; η_{stc} is the PV module's energy conversion efficiency in standard testing conditions (STC), and the efficiency is 16% declared by the manufacturer [31]; and λ is the performance ratio of PV system. This ratio considers all losses from converting solar energy into direct current electricity and then inverting the direct current into alternating current electricity. In order to determine this performance ratio, the operation data of a real rooftop 22 kW$_p$ PV system in Hong Kong was analyzed. This rooftop PV system faces south with a tilted angle of 22.5, which is close to the Hong Kong optimum tilted angle. The annual average solar irradiance received by the PV arrays was 221,278 kWh from 2006 to 2010, and the annual average energy output (AC electricity) was 22,072 kWh. The overall conversion efficiency of the PV system on an annual basis was 10.0%, but the nominal energy conversion efficiency declared by the manufacturer is 13.3%. Thus, the performance ratio can be calculated as 0.75, the figure is also adopted in this study. The calculation result of $E_{potential}$ is about 5981 GWh for each year, which accounts for 14.2% of the total electricity use in Hong Kong in 2011 (the total electricity use was 151,432 TJ in Hong Kong in 2011 [32]). This proportion is much higher than the current set target for renewable energy development (1–2% on or before 2012) in Hong Kong. Thus, according to this result, the policy makers could develop a more positive development target for renewable energy in future and the PV technology has the potential to meet the target. This potential PV electricity output, $E_{potential}$, is also equivalent to reduce about 3,079,815 t[1] of coal or 1,209,259 t[2] of natural gas yearly by replacing the equivalent electricity output, which respectively account for 25% and 54% of the imports of coal and natural gas in Hong Kong in 2011. It will significantly change the current energy structure in Hong Kong.

3. Energy and environmental benefits of PV systems

As stated above, PV technology generally consumes little energy and emits little GHG during operations; thus it appears to be completely clean and without environmental impact. However, PV technology does consume a large amount of energy and does emit a certain amount of greenhouse gases during the system's lifetime, such as in the manufacture of solar cells, PV modules and the balance of system (BOS), transportation, installation, retrofitting, and system's disposal or recycling. In order to thoroughly understand the energy gains and environmental benefits of PV systems, a life cycle assessment (LCA) is adopted by many researchers to comprehensively evaluate the energy and environmental benefits of PV technologies. Some popular LCA indicators, such as the energy payback time (EPBT), greenhouse-gas payback time (GPBT) and greenhouse-gas (GHG) emission rate, are used to effectively measure the sustainability and environmental friendliness of different PV systems.

Although much research concerning the LCA of PV systems has been conducted in recent years [33–41], there are considerable differences in the EPBT and GHG emission rate estimation of PV systems. In addition, little research is based on Hong Kong weather conditions. Thus, based on an estimation of the potential of Hong Kong rooftop PV systems, this study also aims to measure rooftop PV systems' "sustainability" by using LCA indicators of EPBT, GPBT and GHG emission rates. Five typical solar PV modules, i.e. mono-crystalline (mono-Si), multi-crystalline (multi-Si), amorphous silicon (a-Si), CdTe thin film (CdTe) and CIGS thin film (CIGS), were chosen as objects in this particular study.

3.1. Total energy requirement during life cycle

The issue of PV module energy requirement has been studied by many researchers over the last two decades [42–47]. In order to understand how much energy is consumed during a PV system's lifetime, a detailed review of the energy requirements of different PV systems was conducted. The review results, however, show considerable differences in the life cycle energy requirements for either crystalline silicon PV systems or thin film PV systems. For crystalline silicon PV systems, differences revealed in previous literature mainly related to process parameters assumptions, such as wafer thicknesses and wafer losses, as well as silicon purification and crystallization processes [37]. For thin film PV systems, energy requirement differences were mainly caused by the use of different cells and encapsulation types [48]. Based on the review results, a suitable estimation for life-cycle energy requirement of the studied 5 PV modules is presented in Table 5.

Except for the PV modules, the BOS components also consume a certain amount of energy during the system's life cycle. For transportation energy consumption, two cases were considered. In case A, it was assumed that the PV modules were imported from the mainland China; the transportation energy use of a lorry was about 0.004 MJ/kg/km [48] (a module weight of 15 kg/m^2) and an average transportation distance was assumed to be 2000 km. Thus the transportation energy in case A is calculated as 120 MJ/m^2. In case B, the PV modules were assumed by importing from Europe or the US, the transportation energy arising from ocean shipping was about 0.0002 MJ/kg/km, and an average transportation distance was assumed to be 20,000 km. Hence transportation energy in case B is about 60 MJ/m^2. After averaging the above two cases, transportation energy use in this study is assumed to be 90 MJ/m^2. The estimation of the BOS component energy requirement is presented in Table 6.

The total energy requirements of various rooftop PV systems are listed in Fig. 3. The total energy requirements of each square meter of rooftop PV systems are 5555 MJ for mono-Si, 4702 MJ for multi-Si, 2434 MJ for a-Si, 2363 MJ for CdTe and 3177 MJ for CIGS thin film PV system. The mono-Si PV system consumes the largest energy while the CdTe PV system requires the lowest. Except for the PV module's energy use, other two largest energy burdens come from the supporting structure and overhead operation. It is worth noting that the BOS component energy requirement accounts for one third of the total energy requirement of crystalline-Si systems and one half of the thin film PV systems.

3.2. GHG emissions during life-cycle of PV systems

Although there is no GHG emission during the operating of PV systems, a certain amount of greenhouse-gas is emitted during

Table 5
Cumulated energy requirement of the studied 5 PV modules.

Solar PV module type	mono-Si	multi-Si	a-Si	CdTe	CIGS
Energy requirement of PV modules (MJ/m^2)	3775	2952	1039	861	1684

[1] Assuming one ton of coal could generate about 1942 kWh electricity.
[2] Assuming 1000 cubic feet of Natural Gas could generate about 100 kWh electricity.

Table 6
Energy requirement breakdown of BOS components.

Items	Array support +cabling (MJ_p/m^2) [49–50]	Inverter (MJ_p/m^2) [42]	Transportation (MJ_p/m^2)	Installation (MJ_p/m^2)	Overhead oper. and equipment manuf. (MJ_p/m^2) [51]	Take back and recycling (MJ_p/m^2)
Energy requirement of BOS components (MJ/m^2)	600 (roof mounted)	290 (mono) 270 (multi) 135 (a-Si) 212 (CdTe) 203 (CIGS)	90	50	500 (mono and multi) 400 (thin film)	250 240 120 150 150

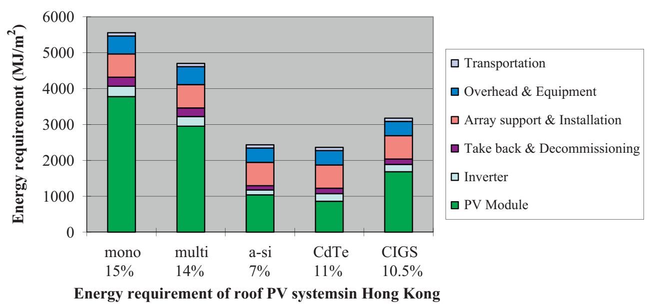

Fig. 3. Total energy requirement of rooftop PV systems in Hong Kong.

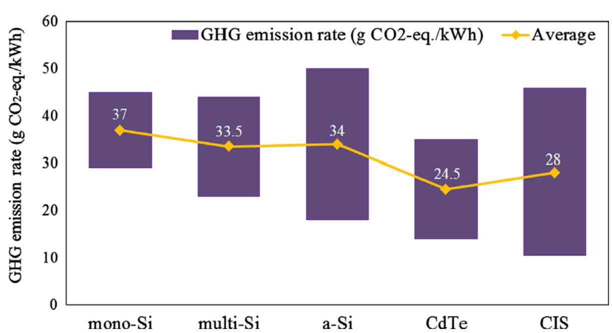

Fig. 4. Review of GHG emission rates of PV electricity generated by various PV systems.

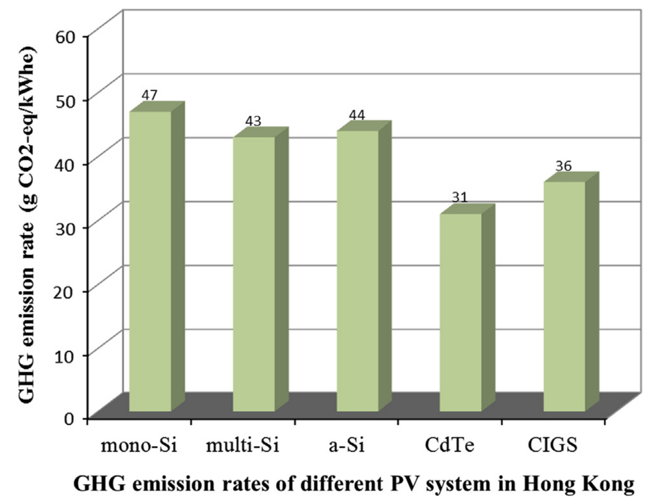

Fig. 5. The estimation of GHG emission rate of rooftop PV systems in Hong Kong.

their life cycle. About 90% GHG emissions are related to the energy use during the life cycle [51–52]. It is very difficult to accurately estimate the GHG emission rate of PV electricity because it is affected by many factors such as the cumulated energy requirement of PV system, electricity mix of the place of origin of PV modules, local solar radiation as well as the PV system's lifespan. A thorough review concerning the GHG emission rate of PV systems was conducted in our previous work [53]. The review results, which had been normalized with the same solar radiation of 1700 $kWh/m^2/yr$, were classified according to the types of solar PV modules and are presented in Fig. 4. It was found that there were considerable differences in estimating GHG emission rate of various PV systems between different researchers [33,35,37,39,41]. Thus, the average GHG emission rate of each kind of PV system in the review results is adopted in this study after being normalized with the local solar radiation of 1333 $kWh/m^2/yr$. Fig. 5 shows the GHG emission rates of different rooftop PV systems in Hong Kong, ranging from 31 to 47 g CO_2-eq/kWh_e. As mentioned before, the GHG emissions are closely related to the energy consumption; thus the mono-Si PV system has the highest GHG emission rate due to its high life-cycle energy requirement. Nevertheless, the mono-Si PV system GHG emission rate still had an order of magnitude less than that of fossil-based electricity in Hong Kong.

3.3. Energy output

Some empirical models can quickly simulate the PV system's energy output. To facilitate the calculation, the following assumptions and simplifications were adopted. All PV systems considered in this study are connected to the utility grid.

(1) The nominal energy conversion efficiencies of the studied PV modules are assumed to be 16% for mono-Si, 15% for multi-Si, 7% for a-Si, 11% for CdTe and 10.5% for CIGS PV modules.
(2) The expected lifetime of the studied PV modules is 30 years, while it is 15 years for the electronic components in the inverter [54].
(3) The performance ratio, including all losses generated the whole system, is 0.75.
(4) It is assumed that the electricity supply system had an overall conversion efficiency of 31% [54] (viz. the conversion efficiency from thermal energy to electricity is 0.31) and the GHG emissions rate of the local electricity mix of the PV module manufacturer is about 1 kg CO_2-eq/kWh.
(5) The GHG emissions rate of the traditional power generation in Hong Kong depends largely on a mixture of fuel types. Based on data provided by China Light and Power Company Ltd. (CLP), the GHG emissions rate is assumed to be 671 g CO_2-eq/kWh[3] for utility electricity in Hong Kong [55].

[3] It is worth noting that the GHG emission of 671 g CO_2-eq/kWh for conventional electricity is a direct emission result, not a life cycle emission result. The life cycle GHG emission of conventional electricity is much higher than 671 g CO_2-eq/kWh. Thus the environmental benefits of PV electricity are actually much better than those of conventional electricity.

Table 7
The annual average generated electricity and the primary energy saving.

PV systems	mono-Si system	multi-Si system	a-Si system	CdTe system	CIGS system
Average annual generated electricity (MJ_e/m^2)	576	540	252	396	378
Yearly saving energy (MJ_p/m^2)	1858	1742	813	1277	1219

According to the above assumptions and simplifications, the annual energy output of per unit area of rooftop PV systems using the studied 5 PV modules can be estimated by

$$E_{unit} = G_{optimal} \times \eta_{stc} \times \lambda \tag{14}$$

where, E_{unit} is the energy output of per unit area of rooftop PV systems, (kWh/m^2); $G_{optimal}$ is the annual total solar radiation incident on the optimum tilted angle, (kWh/m^2); η_{stc} is the energy conversion efficiency of PV systems; λ is the performance ratio which includes all losses generated in the whole system. Taking mono-Si PV system for example, η_{stc} is taken 16%, λ is taken 0.75, $G_{optimal}$ is taken 1333 kWh/m^2. Substituting these values into Eq. (14), the annual energy output of per unit area of mono-Si PV system was calculated to be 160 kWh/m^2. The results for other types of rooftop PV systems are shown in Table 7.

3.4. EPBT, GPBT and EYR

The indicator of energy payback time (EPBT) is defined as the years required for a PV system to generate the same amount of energy (converted into equivalent primary energy) to compensate energy used during its life cycle [56]. The EPBT calculation equation can be presented as

$$EPBT = \frac{E_{input} + E_{BOS,E}}{E_{output}} \tag{15}$$

E_{input} is the primary energy requirement of PV modules during the life cycle, (MJ); $E_{BOS,E}$ is the energy requirement of the balance of system (BOS) components, (MJ); and E_{output} is the equivalent primary energy savings due to PV system's annual electricity generation, (MJ).

The GPBT, shown as Eq. 16, can be defined as the total GHG emissions of the PV modules and its BOS divided by the annual GHG emissions amounts in cases of local electricity mix power plants generating power equivalent to that of the PV system. As with the estimation of energy requirement, it is a great challenge to estimate the life cycle GHG emissions.

$$GPBT = \frac{GHG_S + GHG_{BOS}}{GHG_{output}} \tag{16}$$

where GHG_S is the embodied GHG emissions of PV modules; GHG_{BOS} is the embodied GHG emission of BOS components; and GHG_{output} is the annual GHG emission amounts in the cases where local mix power plants generate the power equivalent to that of the PV system.

As stated above, the EPBT indicator can show how long the PV system can recover the energy use during its life cycle. However, it has important limitations in that it cannot reflect the lifespan of the PV system and also cannot indicate the net energy gain over the system's life cycle [57]. For example, an a-Si PV module has a shorter EPBT than the mono-Si module; however, the latter may have a longer lifespan (about 30 years) than the former (about 20 years). Under this condition, the kind of PV module that may provide more net energy to the user over its lifespan cannot be found if only evaluated by the EPBT indicator. Thus a new energy yield ratio (EYR) indicator was introduced and defined by Watt et al. [58]. The EYR can be defined by the number of times the energy input can be paid back by the PV system over its life cycle. This ratio can be calculated by[57].

$$EYR = \frac{E_{gen} \times L_{PV}}{E_{input} + E_{BOS,E}} \tag{17}$$

where E_{gen} is the equivalent primary energy savings due to annual electricity generation by the PV system; L_{PV} is taken as the designed lifespan of the PV system; E_{input} is the equivalent primary energy input over the life cycle; and $E_{BOS,E}$ is the energy requirement of the balance of system components.

It is obvious that the PV system's energy gains can be evaluated by the EYR indicator. The *EYR* value of specific PV system, greater than unity, means that the system can generate more energy during its lifetime than that is consumed. The *EYR* value less than unity indicates the system cannot return the energy investment during its life cycle. In other words, it is unsustainable in terms of energy payback. Therefore, the unity of EYR is regarded as the break-even point. A PV system is expected to have a higher EYR value. Close relations exist between the EPBT and EYR indicators. Usually, the *EYR* value can be easily calculated by dividing the system's lifetime by the EPBT value.

Based on the data of cumulated energy requirement, the annually generated electricity and GHG emission rate, the indicators of EPBT, GPBT and EYR of the 5 studied rooftop PV systems in Hong Kong, were calculated and are presented in Fig. 6. From this figure, it can be seen that in Hong Kong the EPBTs and GPBTs of the studied rooftop PV systems installed with the optimum inclined angle range from 1.9 to 3.0 and 1.4 to 2.1 years respectively. These statistics are all much less than their lifespans of 30 years. In addition, every year about 3,732,000 t of GHG emissions can be avoided by replacing the equivalent local electricity mix with the potential PV electricity (5981 GWh) generated by rooftop PV systems in Hong Kong. Thus it appears to be possible that the rooftop PV system can play a significant role in energy saving and reducing GHG emission in Hong Kong.

The *EYR*s of the studied 5 PV systems range from 10.0 to 15.8, which indicates that PV systems in Hong Kong can generate approximately at least 10 times of energy requirement during their lifetime. Thus, PV technologies can be definitely regarded as a sustainable energy source. In addition, it is found that the CdTe and CIGS thin film PV systems have better environmental benefits, viz. shorter EPBT and GPBT. While the mono-Si and a-Si PV systems have worse environmental income. This can be partly explained by a respective higher energy requirement and lower energy conversion efficiency, respectively.

4. The levelized cost of energy

Usually, the term of levelized cost of energy (LCOE) can be used to assess the economic feasibility and competitiveness of an energy technology. LCOE can be thought of as the price at which this kind of energy must be sold to achieve cost-recovery over its life cycle. It presents as a net present value in terms of cents/kWh. The LCOE of a PV system can be calculated according to the following equation [59]:

$$LCOE = \frac{Q_{ic} + \sum_{n=1}^{N}\left(Q_o/(1+\gamma_{dr})^n\right) - \left(R_v/(1+\gamma_{dr})^n\right)}{\sum_{n=1}^{N}\left(E_i \times (1-\eta_{dr})^n\right)\Big/\left((1+\gamma_{dr})^n\right)} \tag{18}$$

where, Q_{ic} is the initial cost; Q_o is the annual operation and maintainance cost; γ_{dr} is the real discount rate; R_v is the residual value; E_i is the energy output of a PV system in the first year; and η_{dr} is the PV system's degradation rate. In this study, the system advisor model (SMA), a piece of software developed by NREL, was used to simulate the *LCOE* of rooftop PV systems under different scenarios.

In order to further understand the development state of PV technology, a comparison of the state of PV application in Hong Kong and other districts, viz. Mainland China, Germany and US, was conducted. The key indexes of PV application in these countries and regions are presented in Table 8. It can be seen that both US and Mainland China are rich of solar energy resources due to their vast land area. Relatively speaking, solar energy resources in Germany are much less, which directly results in low life-time energy output of per unit power of PV system there. As shown in Table 8, in Germany, the life-time energy output of per unit power of mono-Si PV system is about 25.1 kWh/W_p, which is only 63% of that in the US. Compared with the above three countries, solar energy resources in Hong Kong are moderate. Although it is not rich of solar radiation, Germany created the largest installation capacity record in the world. At the end of 2012, the PV installation capacity in Germany reached up to 32.4 GW_p, which is far more than those in the US and Mainland China. A matter worthy of reflection is that the installation capacity in Hong Kong is only about 2.5 MW_p, which is completely mismatching to its strong economic strength as well as the intense demands of sustainable urban development. Thus it is the time for energy policy makers in

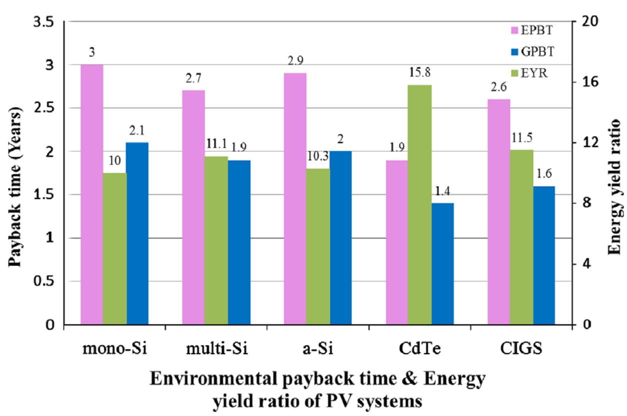

Fig. 6. *EPBT*, *GPBT* and *EYR* of rooftop PV systems in Hong Kong.

Hong Kong to make a plan for solar energy development. The *LCOEs* of PV electricity in the above countries and region are also calculated and presented in Table 8. Owing to the abundant solar radiation resources as well as the lowest installation costs, Mainland China created the lowest *LCOE* of 6.17 cents/kWh, which is close to that of conventional electricity in China and maybe is equal to that of conventional electricity in developed countries. Although the US has much more solar energy resources than that in Germany, its *LCOE* is still higher than that of Germany by about 50%. The main reason caused that is due to its higher installation costs, which is about 2.4 times of that in Germany. Also, due to the high installation costs, Hong Kong has the highest *LCOE*.

4.1. The impact of installation costs on the LCOE

From the above analysis, it can be seen that the PV system's installation costs play a decisive impact on the *LCOE* of PV electricity. In order to further investigate the PV systems' installation costs in Hong Kong and Mainland China as well as giving valuable suggestions to policy makers, project contractors and customers, much information regarding the details of installation costs was collected. The average PV installation cost in Hong Kong is approximately \$5.6/W_p, which is about 3 times higher than that in Mainland China (\$1.48/W_p). A comparison of average installation cost in different countries and regions is presented in Table 8. The installation costs in Germany and the United States were referred to [64], but using the PV module price at the end of 2012 to replace that given in 2011. In general, the PV installation cost in Hong Kong is close to that in the US, but is much higher than that in Mainland China and Germany. Compared with Mainland China and Germany, the main cost differences for Hong Kong are the result of some hardware costs (except for PV module and inverter) and soft costs such as labor costs, project permission and coordination fee, operating overhead and supply chain costs. The major higher hardware costs are probably a result of the following two aspects. Firstly, all hardware in Hong Kong is imported; thus the cost is higher than those in Mainland China and Germany. Both countries produce much of the necessary hardware. On the other hand, the possibility of typhoons means that much support material is necessary for PV installation in Hong Kong to resist their impact. The soft costs in Hong Kong, such as labor cost, permitting fees and coordination costs, operating overheads as well as the demand for profits are much higher than those in Mainland China and Germany, while they are similar to those in the United States.

Table 8
Comparison of some key indexes of PV application in Hong Kong and other countries.

Key indexes	Countries and regions			
	Mainland China	Germany	US	Hong Kong
Solar radiation resource (kWh/m^2)	1000–2200 [60]	900–1200 [60]	1200–2400 [61]	1333
Life-time energy output[a] (kWh/W_p)	35.8	25.1	39.8	31.8
Installation capacity	7.0 GW [62]	32.4 GW[62]	7.2 GW[62]	2.5 MW[63]
LCOE (cents/kWh)	6.17	13.01	19.42	26.09
Total installation costs (\$/W_p)	1.48	2.18	5.23	5.6
PV module (\$/W_p)	0.8	1	1	1
Inverter (\$/W_p)	0.16	0.33	0.42	0.5
Other hardware[b] (\$/W_p)	0.22	0.23	0.47	1.6
Soft costs and profit[c] (\$/W_p)	0.3	0.62	3.34	2.5

[a] In this calculation, the annual solar radiation for China, Germany, US and Hong Kong were taken 1600, 1050, 1800 and 1333 kWh/m^2, respectively, which are the annual average solar radiation resources in these countries or regions. A mono-Si PV module with 16% conversion efficiency was taken as an example in this calculation.
[b] Other hardware includes cable, cable connection, steel support, switches, combiner boxes, monitor system and so on.
[c] Soft costs and profit include labor costs, project coordination fee, operating overhead, supply chain costs, permitting, interconnection and inspection costs, as well as contractor's profits.

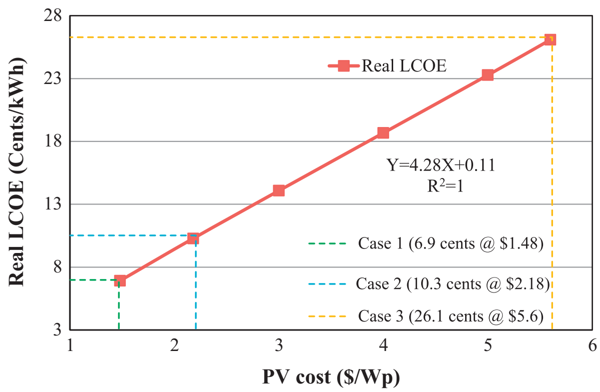

Fig. 7. The relationship of PV installation costs and *LCOE* of PV electricity in Hong Kong.

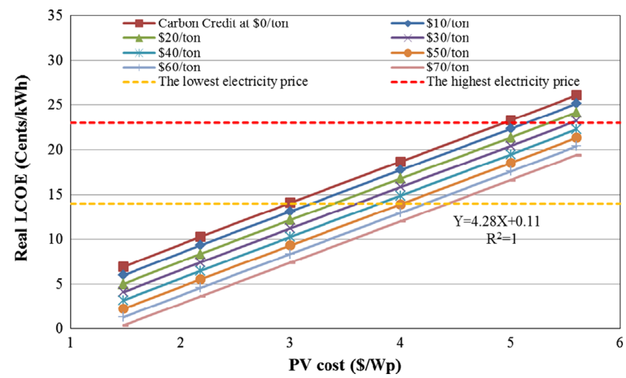

Fig. 8. The sensitivity analysis of the impact of carbon credits' price on the *LCOE* in Hong Kong.

Fig. 7 presents the relationship of PV installation costs and the *LCOE* in Hong Kong. It is shown that the *LCOE* of PV electricity is proportional to installation costs and it decreases with the reduction of installation costs. The installation costs each decline $1/W$_p$; the *LCOE* will drop about 5 cents/kWh. In order to further understand the impact of installation costs on the PV systems' *LCOE* in Hong Kong, the potential *LCOE*s according to the installation costs of Mainland China, Germany and Hong Kong are analyzed and indicated in Fig. 7. Case 1 shows the potential LCOE of rooftop PV system in Hong Kong assuming the installation cost is equivalent to that in Mainland China ($1.48/W$_p$); it is about 6.9 cents/kWh. Case 2 indicates the potential *LCOE* is about 10.3 cents/kWh assuming the installation cost is equivalent to that of Germany ($2.18/W$_p$). Case 3 presents the current real *LCOE* of PV system in Hong Kong. It is about 26.1 cents/kWh, which is calculated by the current average installation cost of $5.6/W$_p$. Currently, the domestic electricity price in Hong Kong is about 14 to 23 cents/kWh depending on the amount of electricity consumption [65]. While with the price rising of fossil fuels, the tariff would rise about 5% annually. Thus even calculated with the current installation cost, the *LCOE* of PV systems in Hong Kong is probably lower than the retail electricity price 1 to 2 years later. If the installation cost is reduced to equal that in Germany in the coming few years by reducing the soft costs, the *LCOE* of 10.3 cents/kWh would be lower than the current retail tariff by 26–55%. With the costs of PV modules and inverters further decreasing, the installation cost in Hong Kong would probably reduce to equal that in Mainland China; hence, the *LCOE* of 6.9 cents would fully compete, without subsidy, with other traditional energy sources. If the environmental benefits of PV electricity, such as much lower GHG emission rates, are considered, the advantage and competitiveness of PV electricity would be strengthened.

4.2. Sensitivity analysis of the price of carbon credits

Since last century, with the concentration of greenhouse gases in the atmosphere continuing to rise, the global warming problem is getting worse and has been attracting the worldwide attention. In order to jointly cope with this challenge, the Kyoto Protocol sets binding obligations on industrialized countries to reduce emissions of greenhouse gases [66]. In order to achieve the emission-reduction goal, this Protocol also introduced a clean development mechanism (CDM) to allow a country with an emission-reduction or emission-limitation commitment under the Kyoto Protocol to implement an emission-reduction project in developing countries [67]. In such projects, the reduced emission can be converted to saleable certified emission reduction (CER) credits, commonly known as carbon credits. A carbon credit represents the permission to emit one ton of carbon dioxide or equivalent amount of other greenhouse gases [68]. Some companies in industrialized countries have to buy such carbon credits to meet their emission-reduction targets. As mentioned above, the GHG emission rate of PV electricity is far less than that of coal-fired electricity; thus investing PV projects can earn saleable carbon credits. Taking Hong Kong for example, for generating per kWh of electricity, a mono-Si PV system can reduce about 0.624 kg GHG emission. Such a PV system can generate about 31.8 kWh electricity per unit power during its life-time, thus the total GHG emission-reduction is 19.8 kg/W$_p$. The reduced emission can be traded as carbon credits in the carbon credit market.

If this carbon credits benefits are considered, the competitiveness of PV electricity would be further strengthened, and its installation cost and *LCOE* would be further reduced with the rising price of carbon credits. In order to understand the impact of rising price of carbon credits on the *LCOE* of PV electricity in Hong Kong, a sensitivity analysis was conducted, and the results are presented in Fig. 8. With the rising price of carbon credits, the *LCOE* of PV electricity is gradually declining. According to the current PV installation costs of $5.6/W$_p$, if the price of carbon credits rises to $30/ton, the *LCOE* will equal to the current highest domestic electricity tariff in Hong Kong. When it rises to $70/ton, the *LCOE* will decline to the average electricity tariff. If the PV installation costs decline to $4/W$_p$ and the price of carbon credits rises to $50/ton, the *LCOE* will be equal to the current lowest domestic electricity tariff (14 cents/kWh). If the PV installation costs decline to $3/W$_p$, the *LCOE* will also equal to the lowest domestic electricity tariff without considering the carbon credits benefits. When the price of carbon credits rise to $70/ton, the *LCOE* will decline to half of the lowest domestic electricity tariff and then the PV electricity can fully compete with the conventional electricity. It is worth noting that if the PV installation costs decline to $1.48/W$_p$ and the price of carbon credits rises to $70/ton, the *LCOE* gets close to 0 cents/kWh, which means that only the carbon credits benefits are enough to return the investment and the PV electricity can be sold free. No matter how much of the installation costs, the *LCOE* will drop about 1 cents/kWh when the price of carbon credits increasing by $10/ton. With the increasing pressure due to global warming, the carbon credits' price is expected to rise, which will result in a continuous declination for the *LCOE* of PV electricity in future.

4.3. Subsidies for PV systems

Nowadays, the PV electricity is still difficult to compete with the conventional electricity in terms of costs. Therefore, many countries have been introducing subsidy policies to support its development. The common policy instruments have been

implemented including feed-in-tariffs (FIT), investment tax credits, subsidies, favorable financing, mandatory access and purchase, renewable energy portfolio standards and public investment [68]. Among these renewable energy policies, feed-in-tariffs maybe is the most effective and successful policy instrument to promote solar PV development [69]. Feed-in-tariff refers to offer a long-term favorable tariff based on the cost of generation to renewable energy technologies, which are relatively expensive and may be unable to compete with conventional electricity [68]. Germany has very successful experience to implement FIT to boost solar PV development by introducing a volume-responsive degression mechanism (or "corridor mechanism") for PV industry, under which the FIT rates decrease according to the installation capacity in prior periods. If more PV systems are installed than the expected amount, the declination range of the FIT rates would be larger and vice versa [70]. This "corridor mechanism" can effectively regulate the volume of annual PV installation under the FIT program. Nowadays, the FIT rates for PV system in Germany range from 10.63 to 15.35 cents/kWh depending on the scale of PV systems [71]. This FIT rate is slightly higher than the current *LCOE* of PV electricity in Germany.

Different from Germany, Mainland China offers one-time initial costs subsidy for the roof-top PV systems which are approved by the Golden Sun programs. The initial costs subsidy is 50% for normal grid-connected PV systems, and 70% for stand-alone PV systems in remote area. This subsidy will cut the current *LCOE* of PV electricity from 6.17 cents/kWh to about 3 cents/kWh. At such *LCOE*, the PV electricity can fully compete with the coal-fired electricity in Mainland China. This is the driving force that boosting the PV installation capacity in Mainland China from about 0.9 GW_p in 2010 to about 7 GW_p in the end of 2012 [62,72]. The United States also implements investment tax credits to support solar energy. The tax credits for PV technology is equal to 30% of expenditures on equipment [68]. This policy plays a significant leverage to PV systems' development in the United Sates. In addition, the state governments also have further supplemented subsidy policies, for example, Los Angeles provides feed-in tariff of 17 cents/kWh for PV electricity [73].

From the above, it can be seen that one of the main reasons why the PV industry can develop rapidly in other countries, especially Germany, is the vigorous support and subsidies provided by the governments in its early development stage. However, there is almost no subsidy for PV systems in Hong Kong. Thus, local policy makers should consider paralleling this approach and providing appropriate subsidies or preferential feed-in tariff to increase users' enthusiasm regarding PV system installation.

4.4. Suggestions for PV development in Hong Kong

The above findings are another encouragement to policy makers to develop related measures or policies to further reduce the soft costs of PV systems as well as provide a suitable subsidy or feed-in tariff. Based on the above installation costs and comparison results from different countries and regions, the following suggestions to enable the reduction of installation costs and promotion of PV application in Hong Kong are proposed:

(1) the government should provide appropriate subsidies and preferential feed-in tariff to increase users' enthusiasm in installing PV systems as well as expand the PV application scale when the *LCOE* of PV electricity is higher than the retail tariff. The effect of large-scale application is beneficial to further reduce hardware costs and non-hardware costs. After PV systems have developed to a certain cost scale, the subsidies could be gradually reduced year by year.
(2) introducing more intense competition mechanisms, such as opening up the PV companies and labor in Mainland China to install PV systems in Hong Kong, to compress the relatively high profit margins of local suppliers and contractors.
(3) training workers and engineers to improve work efficiency and developing more efficient installation methods.
(4) simplifying the processes of grid-connection and reducing the relevant soft costs as much as possible.
(5) effectively attracting private capital and foreign investment (mainly the famous PV suppliers or investors in Mainland China) to develop rooftop PV power plants in Hong Kong by the way of energy management contract (EMC).

5. Conclusions

An in depth study was conducted to investigate the development potential of rooftop photovoltaic (PV) systems in Hong Kong and the ensuing environmental benefits. Based on the modified solar-architectural rules of thumb, the potential PV-suitable rooftop area in Hong Kong was estimated to be 54 km^2. To avoid the negative effect of partial shading from front rows on back rows of PV modules, an array distance of 514 mm should be reserved in real Hong Kong project. After deducting the array distance, the potential installation capacity of rooftop PV systems on all PV-suitable rooftops was estimated to be 5.97 GW_p and accordingly the annual potential energy output was predicted to be 5981 GWh. This accounted for 14.2% of the total electricity used in Hong Kong in 2011. This potential PV electricity output could reduce the import of coal and natural gas by 25% and 54% respectively and also mitigate about 3,732,000 t of greenhouse gas (GHG) emissions yearly by replacing the equivalent local electricity mix.

The energy and environmental benefit of rooftop PV systems during their life cycles was found to be that the energy payback time (*EPBT*) and the GHG payback time (*GPBT*) of different types of PV systems ranged from 1.9 to 3.0 and 1.4 to 2.1 years, respectively, which were all much less than their lifespans of 30 years. Their energy yield ratio (*EYR*) ranged from 10.0 to 15.8, which indicated that the rooftop PV systems could generate at least 10 times the energy requirement consumed during their lifetime. Thus, it can be seen that rooftop PV technology can be considered a sustainable and environmentally friendly renewable energy resource in Hong Kong. Although the current installation cost of PV systems is relatively higher in Hong Kong, however, with the continuing rise of traditional electricity tariff, the unsubsidized levelized cost of energy (*LCOE*) of PV electricity could equal this tariff in 1–2 years. If the carbon credits benefits are considered and the price is assumed to be $30/ton, the *LCOE* of PV electricity will be equal to the current highest domestic electricity tariff in Hong Kong even the current installation cost is as high as $5.6/W_p$. The findings in this paper could provide a theoretical basis for local policy makers to set energy policies, development targets as well as subsidies and feed-in tariffs for PV technology in Hong Kong.

In a word, all by *EPBT*, *GPBT* or *EYR* measurements indicate that in Hong Kong, rooftop PV systems are able to harvest much more energy gains and environmental benefits than their corresponding life cycle investment. In addition, vigorously developing rooftop PV systems in Hong Kong can significantly reduce the reliance on the import of fossil fuels as well as effectively mitigating air pollution problems. Thus, local policy makers should set a series of more proactive energy policies and aggressive development targets for PV technology to cope with the challenges of energy shortage and environment deterioration. If the appropriate subsidies are provided by the government, the carbon credits benefits are considered and the installation cost is further reduced by

simplifying the grid-connection processes and decreasing the soft costs, PV electricity could fully compete with other traditional electricity in the near future in Hong Kong.

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